



## Development and application of PCS gel electrolyte for latent fingerprint detection on various metal surfaces

Wannisa Klinchan

Faculty of Science, Forensic Science Program, Silpakorn University, Thailand

### Abstract

This study presents a novel PCS gel technique for the development of latent fingerprints on various metallic surfaces, including aluminum, stainless steel, brass, alloy, and zinc. The gel formulation, composed of potassium permanganate (KMnO<sub>4</sub>), calcium chloride (CaCl<sub>2</sub>), and silica powder, was optimized to a 1:1:1 ratio (5% w/v KMnO<sub>4</sub>, 1% w/v CaCl<sub>2</sub>, and 5 g silica powder in 10 mL total volume), providing clear ridge details and minutiae suitable for individual identification. The gel consistency allows application on vertical, large, or immovable surfaces, overcoming limitations associated with conventional liquid-based methods. Multi-wavelength flashlight illumination was employed to enhance fingerprint visualization, with blue light (450 nm) producing optimal contrast on both light and dark aluminum surfaces. Comparative analysis indicated that the PCS gel method outperforms traditional black powder techniques in revealing latent fingerprints on metallic surfaces. The proposed method offers a simple, rapid, and cost-effective approach for forensic fingerprint detection, with potential for field application at crime scenes.

**Keywords:** Latent fingerprints, PCS gel, Potassium permanganate, Calcium chloride, Silica powder, Forensic science, Metal surfaces, Multi-wavelength illumination

### Introduction

In modern forensic science, physical evidence has become increasingly critical to the criminal justice system. Every criminal act typically leaves behind trace evidence at the crime scene, and forensic evidence plays a pivotal role in reconstructing events, identifying perpetrators, and exonerating the innocent. Among the various types of forensic evidence, latent fingerprints stand out as a powerful tool for personal identification due to their uniqueness and permanence throughout an individual's life. As such, latent fingerprints are invaluable in crime scene investigations and serve as admissible evidence in court proceedings.

Latent fingerprints at crime scenes are generally classified into two categories: visible fingerprints, which are discernible to the naked eye, and latent fingerprints, which are invisible or barely visible without enhancement. The effective collection and visualization of latent fingerprints require techniques that are appropriate for the specific substrate upon which the fingerprints are deposited. Surface characteristics such as porosity and material composition heavily influence the success of fingerprint development. Over time, various techniques have been developed to enhance latent fingerprints, including powder dusting, superglue fuming (cyanoacrylate fuming), alternate light source (ALS) illumination, chemical staining, and photographic documentation (Sodhi & Kaur, 2001 [28]; Yamashita, 2004). The inappropriate choice or application of these methods may result in the destruction or partial visualization of the latent prints. Therefore, in some instances, multiple methods must be combined—for example, superglue fuming followed by black powder dusting for improved contrast (Bumbrah, 2017; Madkour *et al.*, 2017) [5, 18]

Latent fingerprint development on metallic surfaces is particularly challenging because of their smooth and reflective nature, which often hampers ridge detail visualization. Several studies have explored enhancement

techniques on metals such as copper, aluminum, brass, iron, and zinc, as well as on non-metallic substrates like glass and plastic (Jasuja *et al.*, 2011) [13]. Among the most promising methods are metal sputtering with thin gold or copper films (Fairley *et al.*, 2012) [9], silica gel powder for improved particle adhesion (Singh *et al.*, 2013) [26], the use of gold and silver nanoparticles targeting fingerprint lipids and sweat residues (Ramos & Vieira, 2012) [23], and novel small particle reagent (SPR) formulations incorporating zinc carbonate (Song *et al.*, 2015) [29]. These approaches have significantly advanced the visualization of latent fingerprints on difficult metallic substrates.

Recent advancements in latent fingerprint detection have introduced the use of nanomaterials, fluorescent dyes, and electrochemical methods. Among these, electrochemical techniques—particularly electrochemiluminescence (ECL) imaging—enable high-resolution visualization of ridge patterns, sweat pores, and minutiae (Meng *et al.*, 2020) [19]. Such methods have demonstrated effectiveness across a wide range of substrates, including porous, semi-porous, and non-porous surfaces such as stainless steel, copper, and nickel (Yao *et al.*, 2023) [32]. These innovations represent a significant step forward in enhancing the clarity and reliability of latent fingerprint development.

To address these challenges, this study proposes the development of a novel gel electrolyte-based method for the detection of latent fingerprints on metallic surfaces, including zinc, stainless steel, aluminum, brass, and alloys. The proposed approach offers a simple, cost-effective, and portable solution, making it suitable for movable metallic substrates commonly encountered at crime scenes. By improving the accessibility and practicality of latent fingerprint recovery, this method holds potential to strengthen forensic investigations and provide reliable evidence in criminal justice systems.

## Experimental Method

### 1. Preparation of Samples

Metal sheets of zinc, stainless steel, aluminum, brass, and alloy were cut into square plates measuring 4 cm × 4 cm. Latent fingerprints were deposited by pressing a finger on the prepared metal surfaces with an applied force of approximately 2,000 g for 5 seconds.

### 2. Preparation of Gel Electrolyte Solution (PCS Gel)

The gel electrolyte solution, hereafter referred to as PCS gel, was prepared based on a modified protocol of the potassium permanganate (KMnO<sub>4</sub>)-calcium chloride (CaCl<sub>2</sub>) electrolyte system described by Jasuja *et al.* (2015) [14]. Briefly, KMnO<sub>4</sub> and CaCl<sub>2</sub> were dissolved separately in distilled water at concentrations ranging from 0.5% to 5% (w/v). The solutions were then combined in varying volume ratios to optimize the electrolyte composition. Subsequently, silica powder (SiO<sub>2</sub>; 1-10 g) was incorporated into the mixture, and the resulting solution was gently stirred until a homogeneous gel-like consistency was achieved. The prepared PCS gel was visually inspected to ensure uniformity and suitability for latent fingerprint application.

**Table 1:** Ratios of KMnO<sub>4</sub>, CaCl<sub>2</sub>, and Silica Powder used in the experiment

KMnO <sub>4</sub> (w/v)	CaCl <sub>2</sub> (w/v)	Silica Powder (g)
0.5-5.0%	0.5-5.0%	1.0-10.0

The prepared PCS gel was applied to the sample surfaces using a fine brush to ensure uniform coverage of the deposited latent fingerprints. To determine the optimal conditions for fingerprint visualization and enhancement, the effect of varying time intervals after gel application was systematically investigated.

Following the development period, the latent fingerprints were photographed using a digital camera (Nikon D5600, F-number 4-4.5) under standardized lighting conditions. High-resolution images were captured for subsequent analysis.

The recorded fingerprints were independently evaluated by three latent fingerprint experts with 5, 10, and 20 years of professional experience, respectively. Fingerprint clarity was assessed using a standardized four-point quality scoring system:

0 = No visible latent fingerprint

1 = Poor quality, partial ridge details visible

2 = Fair quality, ridge details visible and suitable for individualization ( $\leq 8$  minutiae)

3 = Good quality, ridge details visible and suitable for individualization ( $\geq 10$  minutiae)

4 = Excellent quality, ridge details visible and suitable for individualization ( $\geq 12$  minutiae)

### 3. Comparison with the Conventional Black Powder Method

To evaluate the effectiveness of the newly developed PCS gel for latent fingerprint visualization, a comparative study was conducted alongside the conventional black powder method. Latent fingerprints were deposited on identical

metallic substrates and subsequently developed using the black powder technique. The resulting fingerprints were documented under the same photographic conditions as those used for the PCS gel, ensuring consistency in image capture.

The clarity and detail of the developed fingerprints were independently assessed by three experienced fingerprint examiners, employing a standardized four-point scoring system. This evaluation focused on two critical aspects of fingerprint quality: the overall visibility of ridge patterns and the identification of minutiae, which are essential for forensic analysis.

Descriptive statistical analysis was employed to compare the two methods, allowing for a clear and systematic assessment of their relative performance. Through this approach, the study aimed to highlight the potential advantages of PCS gel over traditional methods, particularly in terms of enhanced ridge detail and improved minutiae recognition, thereby demonstrating its applicability for forensic investigations.

### 4. Investigation of Flashlight Wavelengths for Latent Fingerprint Visualization on Aluminum Surfaces

Aluminum sheets, both brown and black-colored, were cut into 4 cm × 4 cm squares to serve as experimental substrates. Latent fingerprints were simulated by pressing a fingertip onto each aluminum sample with an applied force of approximately 2,000 g for 5 seconds. The PCS gel, prepared at its optimal formulation, consisted of 0.5% w/v CaCl<sub>2</sub>, 2.5% w/v KMnO<sub>4</sub>, and 5 g silica powder in a total volume of 10 mL, and was applied for latent fingerprint development. A multi-frequency flashlight was employed to investigate the optimal wavelength for enhancing the visibility of latent fingerprints on both aluminum surfaces. The developed fingerprints were photographed using a digital camera, and the captured images were subsequently submitted to three fingerprint examiners for evaluation. The experts assessed ridge details, including minutiae characteristics, and scored the fingerprint clarity according to the previously described quality criteria for latent fingerprints.

## Results

In this study, a gel electrolyte solution (PCS gel) was prepared to investigate the optimal formulation for the development of latent fingerprints on various metallic substrates, including aluminum, stainless steel, alloy, brass, and zinc. The study employed calcium chloride (CaCl<sub>2</sub>), which has been demonstrated in previous research to be effective for detecting latent fingerprints on stainless steel and aluminum surfaces (Ahmad *et al.*, 2019). To enhance fingerprint visibility and improve contrast, potassium permanganate (KMnO<sub>4</sub>) was incorporated due to its strong oxidative properties and distinct coloration. In addition, silica powder was added to convert the electrolyte solution into a gel, allowing it to adhere effectively to surfaces, including elevated or non-movable substrates.

Experimental optimization revealed that the most suitable formulation consisted of 0.5% w/v CaCl<sub>2</sub>, 2.5% w/v

KMnO<sub>4</sub>, and 5 g silica powder in 10 mL of total solution. This composition produced a homogeneous gel within approximately 5 minutes. This specific formulation was selected because it required the lowest amount of calcium chloride while providing optimal visualization of latent fingerprints on all metallic surfaces. Furthermore, the incorporation of silica powder was developed to prolong the contact time of the solution with the substrate by enabling gel application onto the surface. When the PCS gel was applied to different metallic substrates, the resulting latent

fingerprint quality was systematically evaluated using a scoring scale. Expert evaluation of latent fingerprints developed with this formulation yielded a quality score of 4, indicating clear ridge details suitable for forensic identification. Representative formulations of potassium permanganate, calcium chloride, and silica powder, along with their corresponding performance, are presented in Table 2. An example of latent fingerprint development obtained with the optimized PCS gel formulation is illustrated in Figure 1.



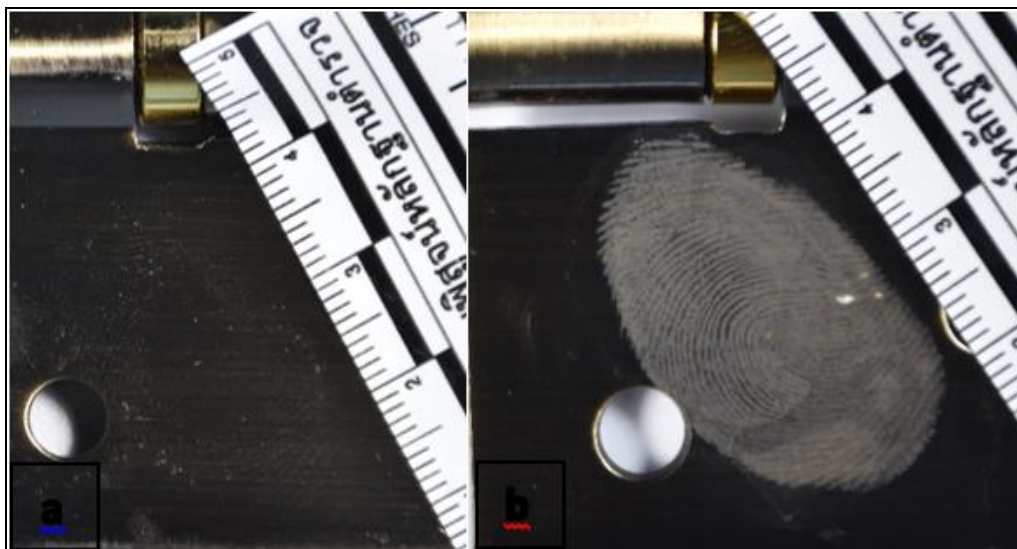
**Fig 1:** Photographic image of a developed latent fingerprint on an aluminum surface, exhibiting a quality score of 4. The fingerprint was obtained using a PCS gel prepared with a 1:1:1 ratio consisting of 5 mL of 5% w/v KMnO<sub>4</sub> solution, 5 mL of 1% w/v CaCl<sub>2</sub> solution, and 5 g of silica powder.

**Table 2:** Ratios of chemical components used in the experimental PCS gel formulations and the corresponding fingerprint quality scores obtained on metal surfaces.

KMnO <sub>4</sub> (%w/v)	CaCl <sub>2</sub> (%w/v)	Silica Powder (g)	Test score
0.5	0.5	5	0
1	0.5	5	1
1.5	0.5	5	1
	0.5		
2	0.5	5	1
	0.5		
2.5	0.5	5	4
	0.5		
3	0.5	5	2
	0.5		
3.5	0.5	5	2
	0.5		
4	0.5	5	2
	0.5		
4.5	0.5	5	1
	0.5		
5	0.5	5	0
	0.5		

Based on the results presented in Table 3, the formulation consisting of 1% CaCl<sub>2</sub> (w/v), 5 mL; 5% KMnO<sub>4</sub> (w/v), 5 mL; and 5 g of silica powder, homogenized into a gel, was found to be the most suitable composition for the development of latent fingerprints on aluminum surfaces. This PCS gel formulation produced ridge details with a quality score of 4, as shown in Figure 2. Consequently, this optimized formulation was applied for further testing on other metallic substrates.

Prior to PCS gel application, the latent fingerprints deposited on metallic surfaces exhibited poor visibility, with ridge details insufficient for individual identification, as confirmed by fingerprint experts (Figure 2). However, after treatment with PCS gel, latent fingerprints became clearly visible and of sufficient quality to reveal characteristic minutiae points, thereby enabling reliable personal identification.

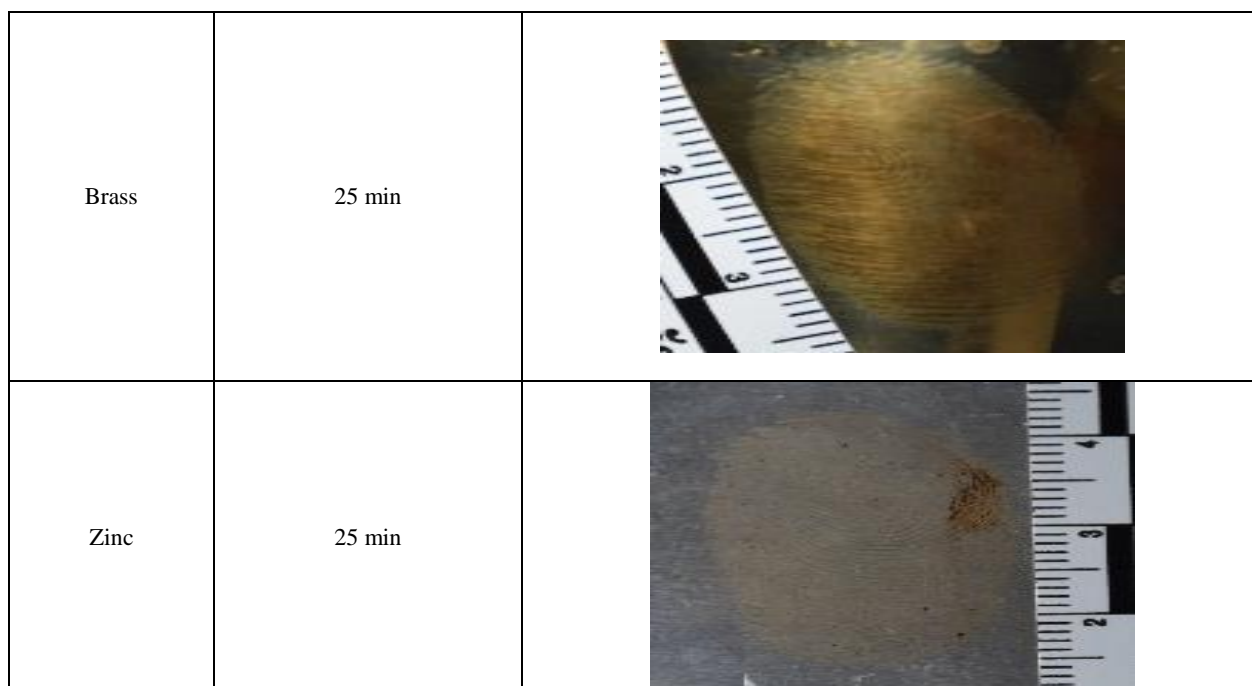


**Fig 2:** Photographic comparison of latent fingerprints on an alloy surface: (a) prior to development with the PCS gel method, and (b) after development using the PCS gel method.

In addition, the study investigated the effect of different time intervals following PCS gel application to achieve optimal visualization across various metallic substrates. The results indicated that the most suitable development times were 15 minutes for aluminum, 20 minutes for stainless steel, and 25 minutes for other metallic surfaces, as summarized in Table 3.

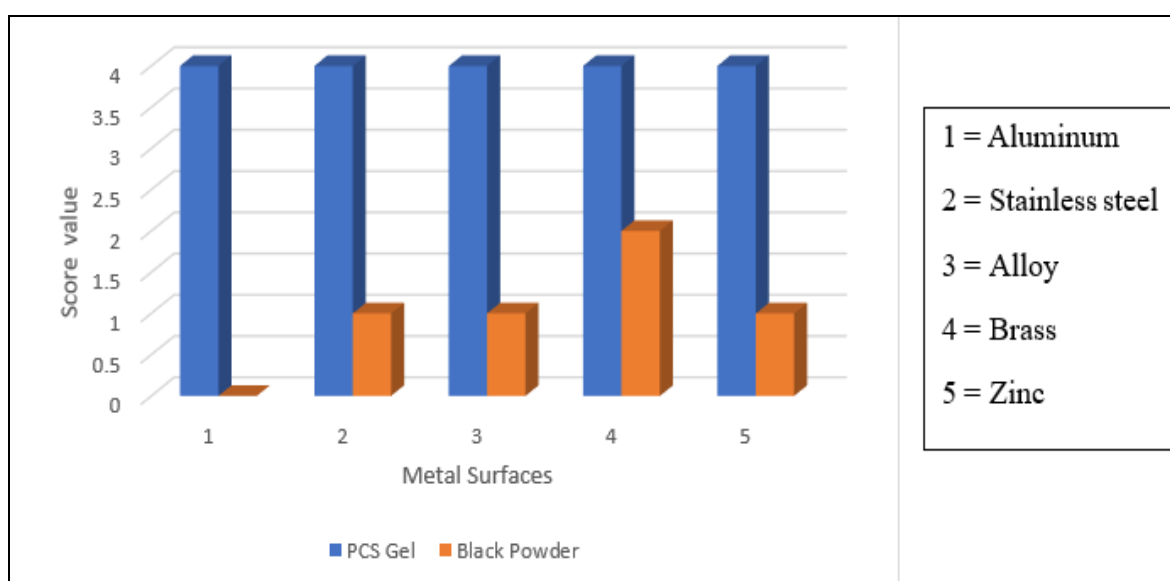
**Table 3:** Photographic representation of latent fingerprints developed using the PCS gel method at a ratio of 1:1:1 (5% w/v  $\text{KMnO}_4$ : 1% w/v  $\text{CaCl}_2$ : silica powder). The developed fingerprints exhibited a quality score of 4 on the evaluated metal surface

Metal surface	PCS gel contact time	Photographic representation of latent fingerprints
Aluminum	15 min	
Stainless steel	20 min	
Alloy	25 min	



In addition, when the optimized PCS gel formulation was applied and compared with the conventional black powder dusting technique, which is commonly used for latent fingerprint detection, it was found that the newly developed

method in this study demonstrated superior performance in visualizing latent fingerprints. This comparison is illustrated in Figure 4.

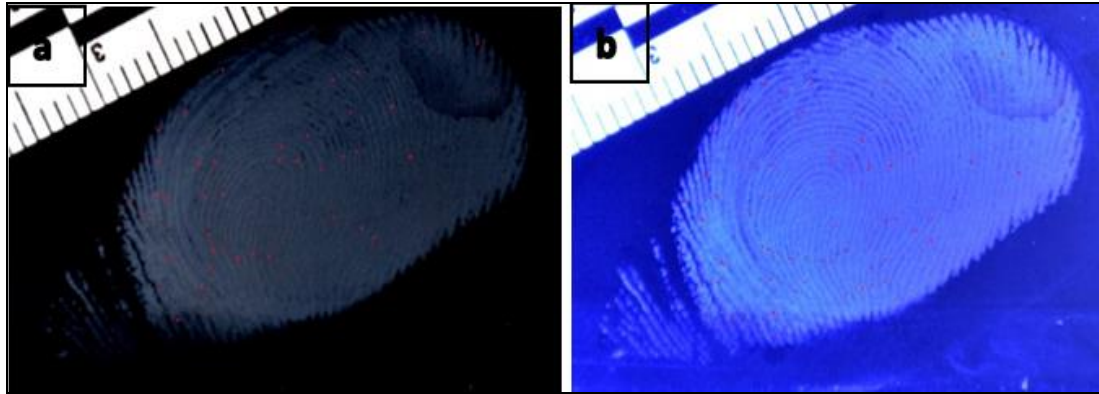


**Fig 4:** Graph illustrating the quality of latent fingerprints developed on various metal surfaces, comparing the PCS gel method with the conventional black powder technique.

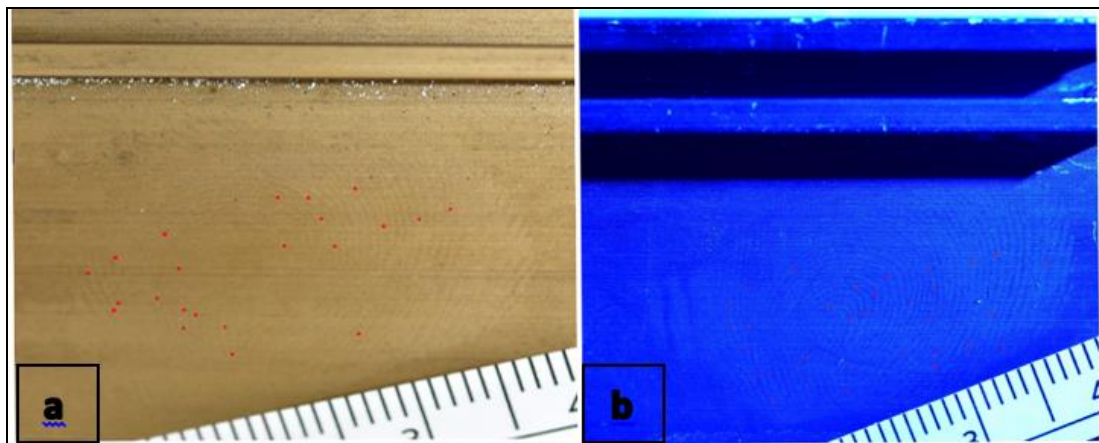
From the study on the optimal contact time for PCS gel application to visualize latent fingerprints on dark-colored and brown aluminum surfaces, it was found that a contact time of 25 minutes was most suitable for the development of latent fingerprints on both surfaces. The study investigated the effect of multi-wavelength flashlight illumination on the visualization of latent fingerprints developed using PCS gel. The gel was prepared with 0.5% w/v calcium chloride, 2.5% w/v potassium permanganate, and 5 g silica powder in a total volume of 10 mL. Latent fingerprints on brown (Figure 2) and black aluminum surfaces (Figure 3) were photographed under different wavelengths: violet (415 nm), blue (450 nm), green (505 nm), yellow (530 nm), orange (590 nm), and red (650 nm).

Evaluation by latent fingerprint experts indicated that blue light (450 nm) provided the optimal illumination for capturing clear images of latent fingerprints on both black and brown aluminum surfaces. The use of blue light enhanced the visibility of ridge details and minutiae, as illustrated in Figures 5 and 6 for black and brown aluminum, respectively, allowing for more accurate identification of fingerprint characteristics.

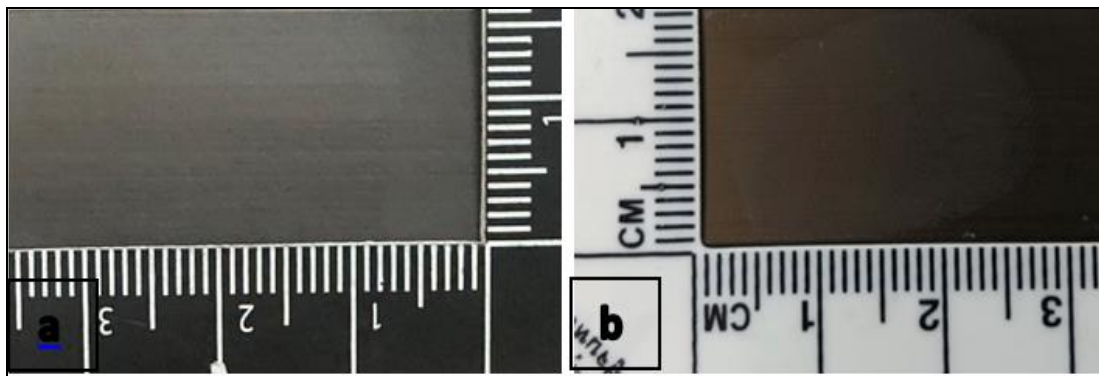
In comparison, the conventional black powder method failed to reveal ridge patterns or minutiae on the brown aluminum surface, as shown in Figure 7, demonstrating the superior performance of the PCS gel combined with blue-light illumination.



**Figure 5-** Photographs showing key features of latent fingerprint impressions on black aluminum surfaces, comparing images taken under (a) white light and (b) blue light (450 nm).



**Figure 6-** Photographs showing key features of latent fingerprint impressions on brown aluminum surfaces, comparing images taken under (a) white light and (b) blue light (450 nm).



**Figure 7-** Photographs of latent fingerprint impressions on brown aluminum surfaces, comparing (a) the black powder method and (b) the PCS gel method.

## Discussion

The present study demonstrates the efficacy of the PCS (Potassium Permanganate-Calcium Chloride-Silica) gel technique for developing latent fingerprints on various metallic surfaces, including aluminum, stainless steel, brass, alloys, and zinc. The gel-based electrolyte formulation—comprising potassium permanganate ( $\text{KMnO}_4$ ), calcium chloride ( $\text{CaCl}_2$ ), and silica powder—enabled enhanced visualization of ridge patterns and minutiae that were previously undetectable using conventional black powder methods (Singh *et al.*, 2012; Jasuja & Sharma, 2016) [11, 25]. The optimized PCS gel formulation (1:1:1 ratio: 5% w/v  $\text{KMnO}_4$ , 1% w/v  $\text{CaCl}_2$ , and 5 g silica powder) provided sufficient adherence and contrast, allowing for effective detection even on dark or hard-to-access surfaces.

Potassium permanganate functions as a strong oxidizing agent, enhancing contrast by reacting with organic residues in latent fingerprint deposits, whereas calcium chloride acts as an electrolyte promoting electrochemical development of fingerprint details. Silica powder increases the viscosity of the solution, transforming it into a gel that adheres effectively to the substrate (Bersellini & Cattaneo, 2010; Broncová *et al.*, 2021) [3, 6]. The gel consistency allows application on vertical, large, or immovable surfaces, overcoming limitations associated with traditional liquid-based methods.

Comparative analysis with conventional black powder revealed that PCS gel significantly improves fingerprint quality, particularly in ridge clarity and minutiae visibility (Fouda-Mbanga *et al.*, 2024) [10]. Black powder often fails to

reveal fine details on smooth, reflective, or dark-colored metallic surfaces, whereas PCS gel provided consistent and reproducible results across all tested metals (Singh, 2014) [24].

Moreover, multi-wavelength flashlight illumination was found to enhance latent fingerprint visualization. Blue light (450 nm) maximized contrast and revealed more minutiae on both light and dark aluminum surfaces, facilitating accurate identification (Wang *et al.*, 2017) [30]. This aligns with prior studies highlighting the importance of specific light wavelengths in fluorescence and contrast enhancement during forensic analysis.

Overall, the PCS gel technique presents several advantages for forensic applications: it utilizes readily available chemicals, is simple and rapid to prepare, adheres well to diverse surfaces, and can be applied to large or immovable metallic objects. These attributes indicate strong potential for field deployment at crime scenes, particularly where conventional methods are insufficient (Canadian Society of Forensic Science Journal, 2016; Singh *et al.*, 2012) [1, 25].

### Conclusion

The PCS gel method is an effective and reliable technique for developing latent fingerprints on metallic surfaces, including aluminum, stainless steel, brass, alloys, and zinc. The optimized formulation (5% w/v KMnO<sub>4</sub>, 1% w/v CaCl<sub>2</sub>, and 5 g silica powder in 10 mL total volume) produced clear ridge patterns and minutiae, enabling accurate individual identification (Singh *et al.*, 2012; Jasuja & Sharma, 2016) [1, 25]. The gel's viscosity allows application on vertical or immovable surfaces, making it particularly suitable for large or awkwardly positioned evidence at crime scenes (Bersellini & Cattaneo, 2010; Broncová *et al.*, 2021) [3, 6].

Comparative analysis revealed that PCS gel significantly outperforms traditional black powder methods, especially in revealing ridge details and minutiae on metallic surfaces (Fouda-Mbanga *et al.*, 2024; Singh, 2014) [10, 24]. The use of blue light (450 nm) further enhanced fingerprint contrast, improving detectability of critical features (Wang *et al.*, 2017) [30]. Overall, the PCS gel technique is simple, rapid, cost-effective, and versatile, making it a promising tool for practical forensic applications (Canadian Society of Forensic Science Journal, 2016) [1].

### Recommendations

Based on the findings of the present study, several avenues for future research are recommended to further enhance the applicability and performance of the PCS gel technique.

First, it is important to investigate the applicability of the PCS gel method across a broader range of metallic substrates. While this study focused on aluminum, stainless steel, brass, alloys, and zinc, other metals commonly encountered in forensic investigations—such as copper, titanium, or coated surfaces—may exhibit different chemical interactions with the gel. Systematic evaluation across diverse metals will provide a clearer understanding of the method's generalizability and robustness, ensuring its reliability in varied forensic contexts.

Second, testing the PCS gel technique on real forensic evidence under different environmental conditions is crucial. Factors such as temperature, humidity, exposure to fire suppression agents, or prior handling of objects may influence the visibility and integrity of latent fingerprints. Evaluating the method in realistic crime scene scenarios will

validate its effectiveness and adaptability in practical forensic applications, moving beyond controlled laboratory conditions.

Third, future research should explore optimization strategies to further improve fingerprint detection. For instance, integrating fluorescent nanomaterials into the gel formulation could enhance sensitivity and contrast, particularly on challenging surfaces or under low-light conditions. Similarly, refining illumination techniques—such as adjusting wavelength selection, intensity, or angle—may improve the visualization of minutiae and fine ridge details, especially on dark, reflective, or contaminated surfaces.

Overall, further studies along these lines will provide deeper insights into the chemical mechanisms and performance characteristics of PCS gel. These efforts will support its development as a reliable, versatile, and field-deployable forensic tool for latent fingerprint visualization on a wide variety of metallic surfaces, ultimately contributing to more accurate and efficient identification of individuals in forensic investigations.

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